

3rd generation SUSY searches at CMS

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The latest results on searches for stop and sbottom squarks are presented. Searches for direct squark production in a variety of decay channels are reviewed. The results are based on 19.5 fb^{-1} of LHC proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ taken with the CMS detector.

I. INTRODUCTION

The standard model (SM) has been extremely successful at describing particle physics phenomena over the last half-century, and the recently discovered boson with a mass of 125 GeV [1, 2] could be the final particle required in this theory, the Higgs boson. However, the SM is not without its shortcomings, for instance one requires fine-tuned cancellations of large quantum corrections in order for the Higgs boson to have a mass at the electroweak symmetry breaking scale [3–5]. This is otherwise known as the hierarchy problem. Due to the magnitude of this fine-tuning, one suspects that there is some dynamical mechanism which makes this fine-tuning “natural”. Supersymmetry (SUSY) is a popular extension of the SM which postulates the existence of a sparticle for every SM particle. These sparticles have the same quantum numbers as their SM counterparts but differ by one half-unit of spin. The loop corrections to the Higgs boson mass due to these sparticles are opposite to those of the SM particles thus providing a natural solution to the hierarchy problem (through the cancellations of the quadratic divergences of the top-quark and top-squark loops). Furthermore, one expects relatively light top and bottom squarks, with masses below around 1 TeV, if SUSY is to be the natural solution to the hierarchy problem [6–9]. In addition, in R -parity conserving SUSY models, the lightest super-symmetric particle (LSP) is often the lightest neutralino $\tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ offers itself as a good dark matter candidate subsequently explaining particular astrophysical observations [10, 11]. In this note, several CMS [12] searches are reported for third generation sparticles using 19.5 fb^{-1} of LHC proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ of which the Feynman diagrams can be seen in Fig. 1.

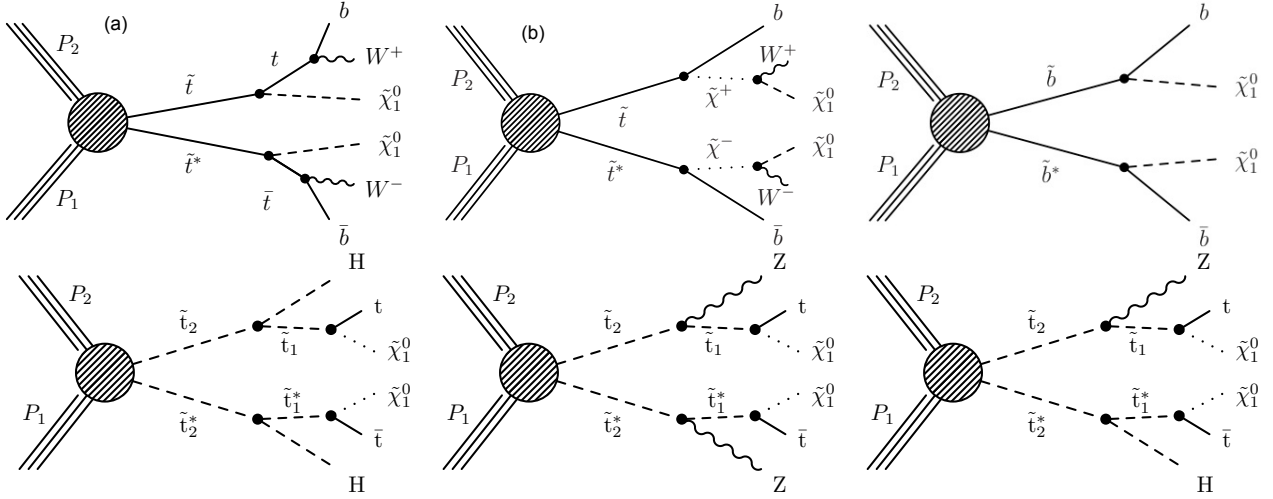


FIG. 1: Top row: Diagram for top-squark pair production for (a) the $\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$ decay mode and (b) the $\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0$ decay mode. (Right) Bottom-squark pair production. Bottom row: Diagrams for the production of the heavier top-squark (\tilde{t}_2) pairs followed by the decays $\tilde{t}_2 \rightarrow H\tilde{t}_1$ or $\tilde{t}_2 \rightarrow Z\tilde{t}_1$ with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. The symbol * denotes charge conjugation.

II. SEARCH FOR DIRECT STOP PAIR PRODUCTION

Searches for top-squark pair production have been performed by the ATLAS Collaboration at the LHC in several final states [13–16], and by the CDF [18] and D0 [17] Collaborations at the Tevatron. In this section two CMS searches using the one-lepton and zero-lepton final states will be discussed.

A. One-lepton final state

For this search two particular decay modes of the top squark (\tilde{t}) namely $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}^+$ are studied. These modes are expected to have large branching fractions if kinematically allowed. Here t and b are the top and bottom quarks, and the neutralinos ($\tilde{\chi}^0$) and charginos ($\tilde{\chi}^\pm$) are the mass eigenstates formed by the linear combination of the gauginos and higgsinos, which are the fermionic superpartners of the gauge and Higgs bosons, respectively. The charginos are unstable and may subsequently decay into neutralinos and W bosons, leading to the following processes of interest: $pp \rightarrow t\bar{t}^* \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$, as displayed in Fig. 1 (top left and top middle). The lightest neutralino $\tilde{\chi}_1^0$ is considered to be the stable LSP, which escapes without detection.

Candidate signal events are required to contain one isolated lepton (e or μ), no additional isolated track or hadronic τ -lepton candidate, at least four jets with at least one b -tagged jet, and $E_T^{\text{miss}} > 100$ GeV; this is referred to as the “preselection”. Signal regions are defined demanding $M_T > 120$ GeV. This requirement provides large suppression of the SM backgrounds while retaining high signal efficiency. Requirements on several kinematic quantities or on the output of boosted decision tree (BDT) multivariate discriminants are also used to define the signal regions, as described below. The analysis is based on events where one of the W bosons decays leptonically and the other hadronically. This results in one isolated lepton and four jets, two of which originate from b quarks. The two neutralinos and the neutrino from the W decay can result in large missing transverse momentum (E_T^{miss}). The major SM background contributions in this search arise from events with a top-antitop ($t\bar{t}$) quark pair where one top quark decays hadronically and the other leptonically, and from events with a W boson produced in association with jets ($W + \text{jets}$). These backgrounds, like the signal, contain a single leptonically decaying W boson. The transverse mass, defined as $M_T \equiv \sqrt{2E_T^{\text{miss}}p_T^\ell(1 - \cos(\Delta\phi))}$, where p_T^ℓ is the transverse momentum of the lepton and $\Delta\phi$ is the difference in azimuthal angles between the lepton and E_T^{miss} directions, has a kinematic endpoint $M_T < M_W$ for these backgrounds, where M_W is the W boson mass. For signal events, the presence of LSPs in the final state allows M_T to exceed M_W . The dominant background with large M_T arises from the “dilepton $t\bar{t}$ ” channel, i.e., $t\bar{t}$ events where both W bosons decay leptonically but with one of the leptons not identified. In these events the presence of two neutrinos can lead to large values of E_T^{miss} and M_T .

To define the signal regions a BDT multivariate approach implemented via the TMVA package [19]. The preselection requirements are applied and the BDT is used to exploit differences of correlation between signal and SM expectations for various kinematic variables. Separate BDTs are trained for the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}^+$ decay modes and for different regions of parameter space. Example BDT outputs after the preselection are shown in Fig. 2 for two of the sixteen BDTs. One notes that the data are in agreement with the MC simulation of SM processes. The full details of the event selection with analysis procedure can be found in Ref. [20].

Overall the observed data yields are consistent with SM expectations and subsequently limits are placed on the signal model of scalar top quark pair production. Our results probe top squarks with masses between approximately 150 and 650 GeV, for neutralinos with masses up to approximately 250 GeV, depending on the details of the model. For the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ search, the results are not sensitive to the model points with $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = M_{\text{top}}$ because the $\tilde{\chi}_1^0$ is produced at rest in the top-quark rest frame. However the results are sensitive to scenarios with $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < M_{\text{top}}$ in which the top quark in the decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ is off-shell, including regions of parameter space with the top squark lighter than the top quark. Furthermore, the acceptance depends on the polarization of the top quarks in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ scenario, and on the polarization of the charginos and W bosons in the $\tilde{t} \rightarrow b\tilde{\chi}^+$ scenario. These polarizations depend on the left/right mixing of the top squarks and on the mixing matrices of the neutralino and chargino [21, 22]. The limits on the top-squark and $\tilde{\chi}_1^0$ masses vary by ± 10 –20 GeV depending on the top-quark polarization. For the $\tilde{t} \rightarrow b\tilde{\chi}^+$ scenario, the acceptance depends on the polarization of the chargino, and on whether the $W \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ coupling is left-handed or right-handed. In the nominal interpretations for the $\tilde{t} \rightarrow b\tilde{\chi}^+$ models presented in Fig. 3, the signal events are generated with an unpolarized chargino and a left/right-symmetric $W \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ coupling.

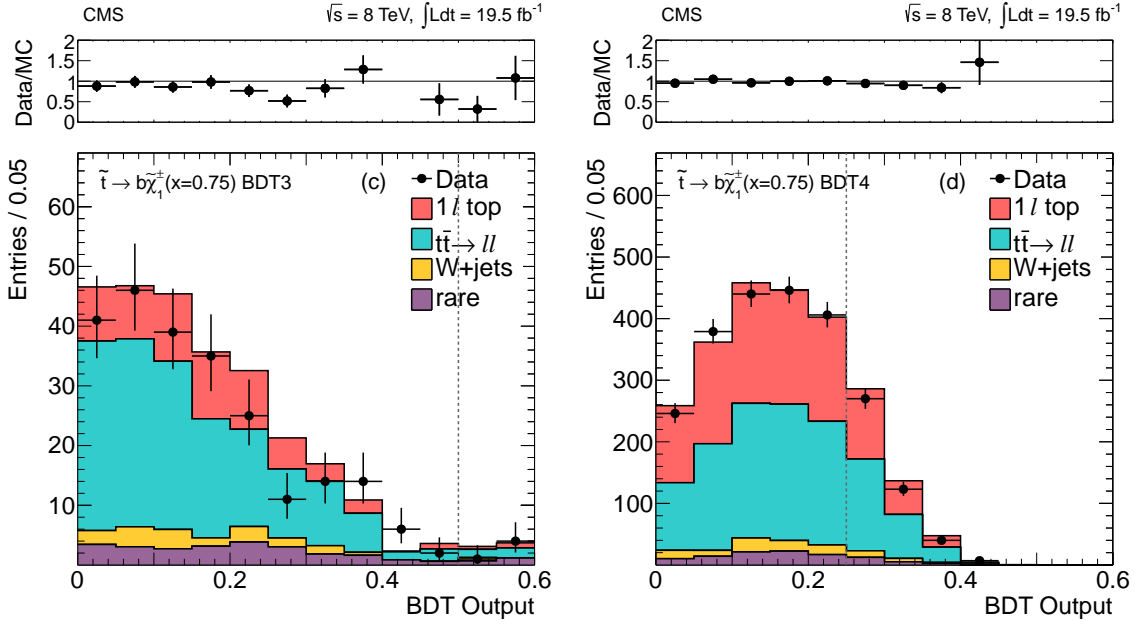


FIG. 2: Comparison of data and MC simulation for the distributions of BDT output and M_T corresponding to the $x = 0.75 \tilde{t} \rightarrow b\tilde{\chi}_1^+$ scenario in two particular training regions.

B. All hadronic final state

Here the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay mode of the top squark (Fig. 1 top left) is studied. The analysis is based on events where both of the W bosons decays hadronically. Candidate signal events are selected by requiring five or more jets, no reconstructed e or μ , at least one jet identified as a b-quark jet, large E_T^{miss} , a reconstructed top quark, and several topological requirements.

The major SM background contributions in this search arise from pairs of top quarks, $t\bar{t}$, with one of the W bosons from the top quarks decaying into a neutrino and a lepton, Z + jets with the Z boson decaying into a pair of neutrinos, and W+jets with the W decaying into a neutrino and a lepton. Events containing a leptonic decay of a W boson still pass the search selection criteria if the e or μ escapes detection or a τ decays hadronically.

Four search regions are defined by requiring $E_T^{\text{miss}} > 200 \text{ GeV}/c$ and $E_T^{\text{miss}} > 350 \text{ GeV}/c$ with at least 1 or at least 2 b-tagged jets. The requirement of $N_{b\text{-jets}} \geq 2$ increases the sensitivity for high mass top squark production. The observed data yields are consistent with SM expectations and subsequently limits are placed on the signal model of scalar top quark pair production. As the four search regions are not mutually exclusive, one of the four search regions is selected at each point in the signal topology scan based on the best expected upper limit for providing the resulting cross section upper limit. The full details of the event selection with analysis procedure can be found in Ref. [23]. The observed cross section upper limits on the signal model considered are shown in Fig. 4 (left).

III. SEARCH FOR DIRECT SBOTTOM PAIR PRODUCTION

Here the search focusses on SUSY particles produced in proton-proton collisions with a large imbalance in transverse momentum and two energetic jets one or both of which are identified as originating from bottom quarks (b-jets). This final state is motivated by the production of pairs of bottom squarks (\tilde{b}) where each \tilde{b} decays into a bottom quark and a $\tilde{\chi}_1^0$ (see Fig. 1 top right). Candidate signal events are selected by requiring two central jets with $p_T > 70 \text{ GeV}$ and $|\eta| < 2.4$, one or both of the leading jets are required to be b-jets, no reconstructed e or μ , $H_T > 250 \text{ GeV}$, $E_T^{\text{miss}} > 175 \text{ GeV}$, and several topological requirements. To suppress SM processes such as $t\bar{t}$ and $W(\ell\nu)$ +jets, the invariant transverse mass of the sub-leading jet and the missing transverse momentum, as defined in Equation 1, is required to be greater than 200 GeV.

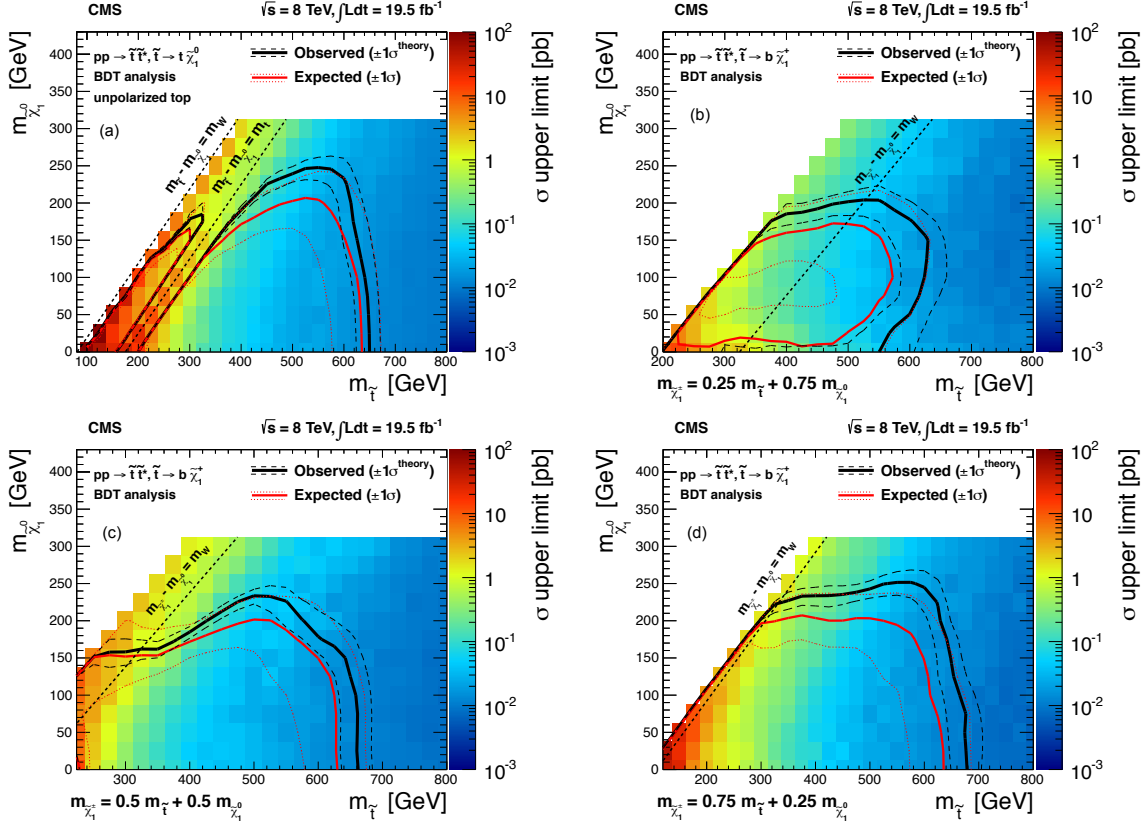


FIG. 3: Interpretations using the primary results from the BDT method. (a) $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ model; (b) $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ model with $x = 0.25$; (c) $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ model with $x = 0.50$; (d) $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ model with $x = 0.75$; The color scale indicates the observed cross section upper limit. The observed, median expected, and ± 1 standard deviation (σ) expected 95% CL exclusion contours are indicated. The variations in the excluded region due to $\pm 1\sigma$ uncertainty of the theoretical prediction of the cross section for top-squark pair production are also indicated.

$$M_T(J_2, E_T^{\text{miss}}) = \sqrt{[E_T(J_2) - E_T^{\text{miss}}]^2 + [\mathbf{p}_T(J_2) - \mathbf{E}_T^{\text{miss}}]^2}, \quad (1)$$

The distribution of $M_T(J_2, E_T^{\text{miss}})$ is expected to have a kinematic edge at the mass of the top quark when the jet and E_T^{miss} originate from semileptonic decay of a top quark. Events are characterized using the boost-corrected contranverse mass (M_{CT}) [24, 25]. For processes with two identical decays of heavy particles, $\tilde{b} \rightarrow J_i\tilde{\chi}_1^0$, the M_{CT} is defined as:

$$\begin{aligned} M_{CT}^2(J_1, J_2) &= [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p}_T(J_1) - \mathbf{p}_T(J_2)]^2 \\ &= 2p_T(J_1)p_T(J_2)(1 + \cos \Delta\phi(J_1, J_2)), \end{aligned} \quad (2)$$

To obtain sensitivity in multiple regions across the $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0})$ plane, a total of eight exclusive search regions are defined using M_{CT} and the number of b jets ($N_{b\text{-jets}}$), as summarized in Table I.

TABLE I: Definition of eight exclusive search regions.

No. of b-jets	M_{CT}	M_{CT}	M_{CT}	M_{CT}
$N_{b\text{-jets}} = 1$	< 250 GeV	250 - 350 GeV	350 - 450 GeV	> 450 GeV
$N_{b\text{-jets}} = 2$	< 250 GeV	250 - 350 GeV	350 - 450 GeV	> 450 GeV

The major SM background contributions in this search arise from $Z(\nu\bar{\nu})$ +jets, an irreducible background; $t\bar{t}$, single top and $W(\ell\nu)$ + jets events, where a W decays to e or μ (directly or via a τ decay) which survives the lepton veto because it is misidentified, nonisolated or is out of kinematic acceptance, or a τ that decays hadronically and is reconstructed as a jet; and QCD multijet events where semileptonic decays of b -quark jets or mismeasurements of jets can result in large missing transverse momentum. The full details of the event selection with analysis procedure can be found in Ref. [26]. The observed data yields are consistent with SM expectations and subsequently limits are placed on the signal model of scalar bottom quark pair production show in Fig. 4 (right).

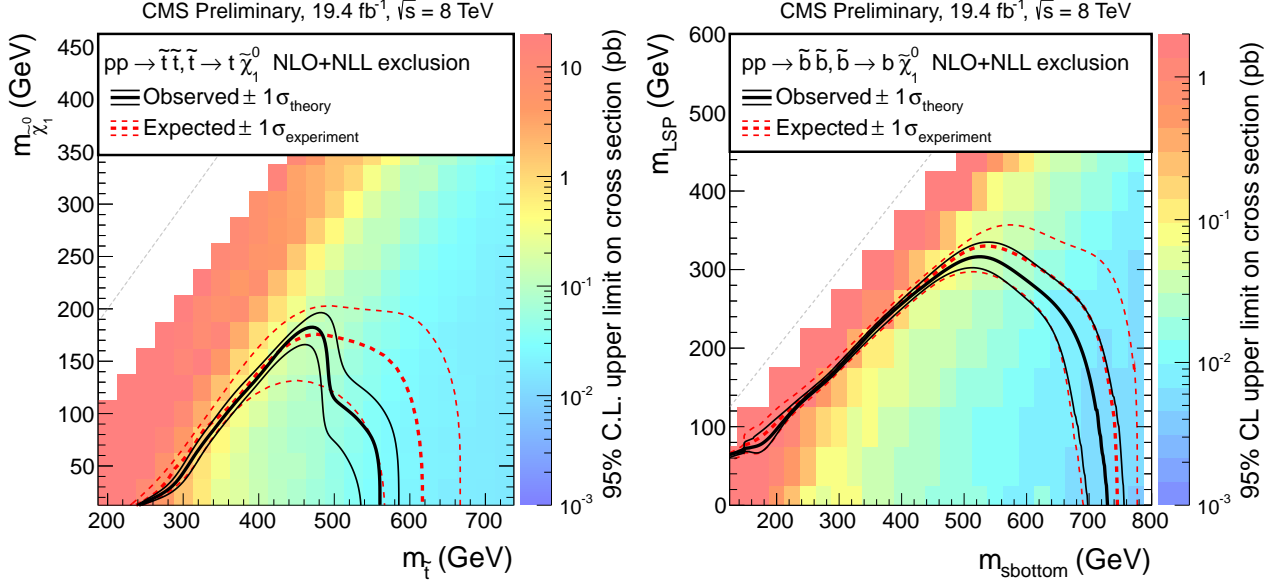


FIG. 4: Combined 95% C.L. exclusion limits for (left) top squark pair production in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay channel with the all hadronic search and (right) bottom squark pair production. The plot shows the expected limit as a red dashed line. The observed limit is shown as a black solid line. The dashed red (solid black) lines represent the expected (observed) exclusion contours at 95% CL. The total experimental uncertainty is shown around the expected limit contour as dashed red lines, and the theoretical uncertainty is shown around the observed limit contour as thin black lines.

IV. SEARCH FOR TOP-SQUARK PAIR PRODUCTION WITH HIGGS AND Z BOSONS

Searches for direct top-squark production at the LHC have focused mainly on the simplest scenario, in which only the lighter top-squark mass eigenstate, \tilde{t}_1 , is accessible at current collision energies. In these searches, the top-squark decay modes considered are those to a top quark and a neutralino, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$, or to a bottom quark and a chargino, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0$. These two decay modes are expected to have large branching fractions if kinematically allowed. The lightest neutralino, $\tilde{\chi}_1^0$, is the lightest SUSY particle (LSP) in the R-parity conserving models considered; the experimental signature of such a particle is missing transverse energy (E_T^{miss}).

The sensitivity of searches for direct top-squark production is, however, significantly reduced in the $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ decay mode for the region of SUSY parameter space in which $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t$. For example, in Ref. [20], the region $|m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t| \lesssim 20$ GeV is unexplored. In this region, the momentum of the daughter neutralino in the rest frame of the decaying \tilde{t}_1 is small, and it is exactly zero in the limit $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = m_t$. As a result, the E_T^{miss} from the vector sum of the transverse momenta of the two neutralinos is typically also small in the laboratory frame. It then becomes difficult to distinguish kinematically between \tilde{t}_1 pair production and the dominant background, which arises from $t\bar{t}$ production. This region of phase space can be explored using events with topologies that are distinct from the $t\bar{t}$ background. An example is gluino pair production where each gluino decays to a top squark and a top quark, giving rise to a signature with four top quarks in the final state [27, 28].

This search targets the region of phase space where $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t$ by focusing on signatures of $t\bar{t}HH$, $t\bar{t}HZ$, and $t\bar{t}ZZ$ with E_T^{miss} . These final states can arise from the pair production of the heavier top-squark mass eigenstate \tilde{t}_2 . There are two non-degenerate top-squark mass eigenstates (\tilde{t}_2 and \tilde{t}_1) due to the mixing of the SUSY partners \tilde{t}_L and \tilde{t}_R of the right- and left-handed top quarks. The \tilde{t}_2 decays to \tilde{t}_1 and an H or Z boson, and the \tilde{t}_1 is subsequently assumed to decay to $t\tilde{\chi}_1^0$, as shown in the bottom row of Fig. 1. Other decay modes such as $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ are largely covered for $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \simeq m_t$ by existing analyses [20]. The final states pursued in this search can arise in other scenarios, such as $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0$, with $\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$. The search is also sensitive to a range of models in which the LSP is a gravitino. The relative branching fractions for modes with the H and Z bosons are model dependent, so it is useful to search for both decay modes simultaneously. In the signal model considered, \tilde{t}_2 is assumed always to decay to \tilde{t}_1 in association with an H or Z boson, such that the sum of the two branching fractions is $\mathcal{B}(\tilde{t}_2 \rightarrow H\tilde{t}_1) + \mathcal{B}(\tilde{t}_2 \rightarrow Z\tilde{t}_1) = 100\%$. Other possible decay modes are $\tilde{t}_2 \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t}_2 \rightarrow b\tilde{\chi}_1^+$.

The four main search channels contain either exactly one-lepton, two leptons with opposite-sign (OS) charge and no other leptons, two leptons with same-sign (SS) charge and no other leptons, or at least three leptons (3 ℓ). The channels with one-lepton or two OS leptons require at least three b jets, while the channels with two SS leptons or 3 ℓ require at least one b jet. The major SM background contribution in this search arise from $t\bar{t}$ pair production, which has two b quarks and either one-lepton or two OS leptons from the $t\bar{t} \rightarrow \ell\nu q\bar{q}b\bar{b}$ or $t\bar{t} \rightarrow \ell\nu\ell\nu b\bar{b}$ decay modes, where q denotes a quark jet. The sensitivity to the signal arises both from events with additional b quarks in the final state (mainly from $H \rightarrow b\bar{b}$), and from events with additional leptons from H or Z boson decays. The full details of the event selection with analysis procedure can be found in Ref. [29]. The observed data yields are consistent with SM expectations and subsequently limits are placed on top quark pair production (see Fig. 5).

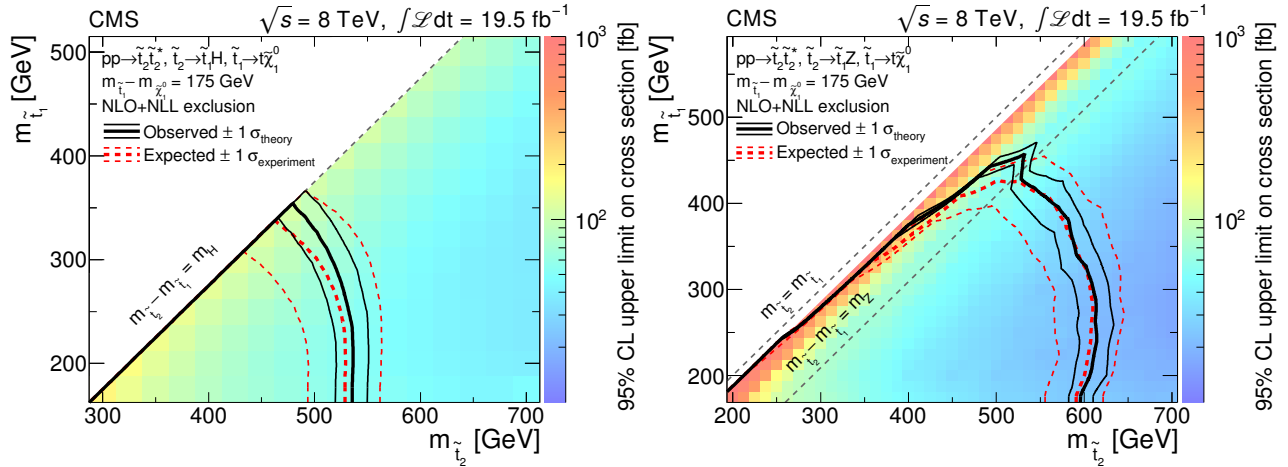


FIG. 5: Interpretation of the results in SUSY simplified model parameter space, $m_{\tilde{t}_1}$ vs. $m_{\tilde{t}_2}$, with the neutralino mass constrained by the relation $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 175$ GeV. The shaded maps show the upper limit (95% CL) on the cross section times branching fraction at each point in the $m_{\tilde{t}_1}$ vs. $m_{\tilde{t}_2}$ plane for the process $pp \rightarrow \tilde{t}_2 \tilde{t}_2^*$, with $\tilde{t}_2 \rightarrow H\tilde{t}_1$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t}_2 \rightarrow Z\tilde{t}_1$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. In these plots, the results from all channels are combined. The excluded region in the $m_{\tilde{t}_1}$ vs. $m_{\tilde{t}_2}$ parameter space is obtained by comparing the cross section times branching fraction upper limit at each model point with the corresponding NLO+NLL cross section for the process, assuming that (a) $\mathcal{B}(\tilde{t}_2 \rightarrow H\tilde{t}_1) = 100\%$ or (b) that $\mathcal{B}(\tilde{t}_2 \rightarrow Z\tilde{t}_1) = 100\%$.

V. SUMMARY

CMS has carried out several searches for superpartners of third generation fermions with an integrated luminosity of 19.5 fb^{-1} . No excess in data with respect to the SM expectation has been observed so far. However, searches in large regions of the parameter space for natural SUSY are still in progress. These searches are challenging due to similarity with the $t\bar{t}$ final state for low stop masses, and due to the low cross sections for higher stop mass values. Subsequently, new results obtained at $\sqrt{s} = 13 \text{ TeV}$ in 2015 will be looked upon with eager anticipation.

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